RISK ANALYSIS METHODOLOGY
APPENDIX O

Estimating Potential for Life Loss Caused by Uncontrolled Release of Reservoir Water

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Risk analyses and other dam safety studies often require that an estimate be made of the potential life loss that would result from dam failure. Three primary factors affect potential life loss that could be caused by the various dam failure scenarios: 1) the number of people occupying the area inundated by a dam-break flood, 2) the amount of warning provided to the people exposed to dangerous flooding, and 3) the intensity of the flow to which people are exposed. In "A Procedure for Estimating Loss of Life Caused by Dam Failure", DSO-99-06, Wayne Graham establishes Reclamation's procedure for estimating potential life loss, incorporating these seven basic steps to varying degrees:

· Determine dam failure scenarios to evaluate, such as failure during major floods or during earthquakes.

· Determine the area flooded for each dam failure scenario.

· Determine if the number of people exposed to dam-break flooding is affected by the time the dam-break event takes place (such as day or night, weekday or weekend, summer or winter).

· Estimate likely ranges for population at risk (PAR) for each scenario.

· Determine when dam failure warnings would be initiated in relation to the time it would take for the flood wave to arrive at the locations of the various populations at risk.

· Apply empirically based equations or algorithmic methods for estimating fatalities based on population at risk, flood intensity, and warning time.

· Report potential life loss as a range of values that incorporates significant contributors to uncertainty.

In DSO-99-06, Wayne Graham presents the procedure's basic structure and focuses on the rationale for choosing the fatality rate ranges assigned to his 15 combinations of flood severity, warning time, and flood severity understanding. The purpose of this appendix is to provide guidance in using Wayne Graham's method to estimate the potential life loss consequences during a risk analysis. Types of information typically available at Reclamation are described, other potential sources for this information are suggested, and some means to evaluate the information are provided. Most of what is discussed in this appendix pertains to a level of effort that one might undertake to prepare for a more rigorous risk analysis, involving a team for a period of a week or more. Some suggestions are offered to point out shortcuts that might be taken in a less rigorous CFR-level risk analysis, but those using the shortcuts ought to understand the nature of the simplifying assumptions they may be using. There is another document specifically directed to the steps one might take to prepare the Consequences Section of the CFR.

I. Choose appropriate failure scenarios

The way in which a dam fails can influence potential life loss by increasing or decreasing the area inundated by flooding, by affecting the flood wave intensity and development time, and by affecting the warning time available for evacuation. Certainly, the highest potential life loss would come from a sudden, rapid failure as might occur if a thin arch concrete dam exposed to excessive earthquake loading suddenly bursts. A liquefaction induced flow slide resulting in immediate overtopping of an embankment dam might be another example of an extremely rapid failure. However, even though a liquefaction-induced flow slide might allow instantaneous overtopping, it may be that the initial release over the failed section is nowhere near the flow quantity needed to wash away buildings. The initial release may not even exceed safe channel capacity. Subsequent breach formation could be very rapid (on the order of 15 to 30 minutes), but it would not be instantaneous. If the majority of the embankment itself liquefies, the entire embankment could disappear instantaneously.

At the other extreme, it might take hours or even days to fail a highly-plastic, well-compacted embankment dam or a well-filtered rockfill dam that has an extremely large flow-through capacity. The resulting peak flow released may not be as intense as that released by a more rapid dam failure, particularly if the reservoir storage is small at the time of the event. Early detection of the incipient dam failure may be more likely during a slowly developing failure mode than during a quick one, and successful intervention may be possible in the early stages of this type of potential dam failure incident.

While setting up the potential life loss study, consider how many different ways the life threatening floods could be formed by the given failure modes. Consider best case/worst case scenarios for breach development time and warning time. If the logical event sequence has already been determined and failure probabilities quantified, spend the most effort on the most significant event tree end branches. These might be the ones associated with the highest failure probability. Or, they may be ones with a smaller failure probability but with the potential to cause extremely large life loss.

Judgement is required to determine the number of scenarios to be evaluated. Sometimes a worst case scenario can be quickly evaluated and found to cause insignificant risk. In this case, little effort is called for to wrap up the risk analysis. In other cases, the scenario choice is much more influential. Breaking the problem into too many pieces, though, can cause unnecessary confusion to peer reviewers and decision makers. Balance the effort to keep the analysis as simple as possible yet as complicated as necessary to reach reasonable conclusions.

II. Determine area flooded for each failure scenario

A. Information Sources for Dam-Break Flood Inundation Maps / Flood Intensity

In order to determine a population's exposure to dam-break flooding, and to determine the likelihood that severe flooding will kill them, a flood inundation boundary map and a sense of the flood intensity are needed. The boundary map and flood intensity information should be related to the failure mode being analyzed.

If only currently available information is to be used, flood inundation boundary maps typically available for Reclamation dams are found in the dam's Standing Operating Procedures (SOP). More recently, some of the inundation maps have been transformed into Geographic Information System (GIS) format. Most of the existing inundation boundary maps were generated by superimposing a dam-break flood upon the spillway and outlet works releases that might take place during a Probable Maximum Flood (PMF). The boundary could be viable for flood-related overtopping failures, and for some sunny day failures where very little freeboard typically exists. However, for sunny-day failures where large freeboard is the norm, the inundation area boundaries will be too extensive and will cause PAR estimates that are too large. One might use the PMF boundary anyway, knowing the estimate would be conservative to form a preliminary understanding of the potential life loss. If valid conclusions regarding potential recommendations for action can be drawn from the preliminary estimate, there may be no need to conduct additional investigations.

If the need for greater accuracy is identified, additional dambreak or flood routing studies can be conducted. In the absence of further numerical analysis, some simple adjustments to the inundation boundaries can be made. One could estimate the peak outlfow from a sunny-day failure using the empirical relationships described in "Prediction of Embankment Dam Breach Parameters", DSO-98-004, by Tony Wahl. The ratio of the peak outflow from a sunny-day dam break to the peak outflow from the PMF dam break multiplied by the reported flow depth at any cross section in question might give a crude estimate for the contour elevation that would bound the sunny-day dam failure flood.

Dam break flood analysis consists of two main parts: the breach formation process and the routing of the dam-break flood. (A third aspect, breach initiation, is discussed in "Estimating Risk of Internal Erosion and Material Transport Failure Modes for Embankment Dams", Appendix E, Risk Analysis Methodology. This third aspect does not pertain to mechanisms of dam break flood analysis, but does influence time-of-breach-formation considerations. More on this in the warning time discussion below.) The various aspects of breach formation depend on erosive character of the embankment or foundation materials, the geometry of the dam, the failure mode, and the volume of water stored in the reservoir.   If information is not available or a more refined dam break analysis is required, start with an estimation of dam breach parameters. DSO-98-004 presents the various analytical and empirical methods available to estimate breach formation parameters as well as methods to estimate peak outflow and breach development time. Key input parameters to a dam break analysis include breach height, width, bottom elevation, side slopes, and breach development time. Analysis output could include either a peak flow or a dam-break flood hydrograph.

The dam-break flood routing is typically modeled in a one-dimensional computer simulation using the output hydrograph obtained from the dam-break analysis. Cross sections of elevations at various key river stations downstream from the dam are generated, and open channel flow equations are used assuming a linear interpolation between stations. Output includes the travel time to the cross section, and the flow velocity and depth. The results are simplistic, are possibly suitable for some canyon situations, but are probably far from the truth when the floodwaters spread out over extensive flat lands. If refined analysis is necessary, two-dimensional modeling can be done, but the analysis is expensive and time consuming. A note of caution: the dam break model typically used by Reclamation to create the dam break flood hydrograph (BOSS DAMBREAK) will create a hydrograph based on the breach parameters and the breach development time that are input by the analyst. There is no check internal to the program that determines if it is physically possible to remove the volume of material encompassed by the specified breach parameters in the specified time. Anyone using dam break flood hydrographs for potential life loss determinations should be aware of the assumptions that were made to create the hydrographs, and verify that the assumptions made are sensible.

Water depth and flow velocity, and the rate at which a deep, fast-flowing water situation might develop all affect potential life loss. Flows that can demolish buildings are more life threatening than flows that simply move buildings from their foundations. Likewise, flows that move buildings from their foundations are more severe than situations where the water rises gradually to a home's second story or where depths and flows are such that most people could easily walk away through the water. Each situation has a different capacity to cause life loss.

Graham (DSO-99-06) has suggested an index property, net discharge (Q) divided by the maximum width of flooding, to provide a measure of flood intensity. He writes: "Although the parameter is not representative of the depth and velocity at any particular structure, it is representative of the general level of destructiveness that would be caused by the flooding. The parameter should provide a good indication of the severity (potential lethality) of the flooding. As the peak discharge from the dam failure increases, the value of the parameter increases. As the width of the area flooding narrows, the value of the parameter again increases." If net discharge and flooding width information is available, calculate this index ratio. Graham suggests a ratio of 50 ft^2/sec as the boundary between moderate intensity flooding and low intensity flooding.

The inundation boundary for hydrologic events deserves special attention. The potential life loss considered should be a difference between what might happen if the dam were to not fail and what might happen if the dam were to break. Two inundation boundaries must be known: the area inundated by spillway and outlet works releases just prior to dam break, and the additional area inundated by the dam break. The additional area inundated by the dam break is what should be used to estimate the PAR. If there is only a PMF dam-break inundation map and no map showing inundation from pre-dambreak releases, a crude approximation similar to the one described above for the sunny day dambreak approximation might be useful.

The estimation of PAR incrementally threatened by dam break flooding during hydrologic events assumes that the entire PAR threatened by large spillway and outlet works releases will have already evacuated their homes. Note that people's actions during the Johnstown flood would indicate this assumption may not always be valid. Some streets in the city of Johnstown were inundated by as much as 10 feet of water prior to the arrival of the dam failure flood wave. Some people had moved to the second story of their houses to wait for the flood waters to recede when the wall of water from the dam-break flood arrived to demolish their houses. This possibility might be considered in an upper bound PAR estimate when analyzing hydrologic failure modes.

B. Suggestions for CFR level risk analyses

1. Use the current SOP inundation maps as a first cut. Sometimes there is only an inundation map for a PMF event. If this is as far as it goes, report a judgement of the potential differences in inundation boundaries expected between dambreak with PMF and dambreak under sunny day conditions.
2. If there is typically a large enough amount of freeboard at the dam to believe there will be a gross over-estimation of inundation boundaries, make an adjustment to the inundation boundary. Base the adjustment on a ratio of peak flow from a breach assuming existing storage conditions to the peak flow from a breach assuming storage conditions associated with the PMF. An alternative is to knowingly use a conservative estimate for the CFR but recommend additional dambreak and flood routing studies be done to improve the estimate if an assessment of the risk with respect to Reclamation's Guidelines warrants such a study.

III. Determine if time of failure influences exposure to flooding

Time factors include the season of the year, the day of the week, and the time of day. The highest life loss has been observed to take place closest to the dam where warning time is typically least and flooding intensity tends to be greatest. Quite often, seasonal or day use facilities exist just below Reclamation's dams. Campgrounds may be unused in the winter and heavily used in the summer, especially on weekends. Highway usage and residence occupancy may vary seasonally as well.

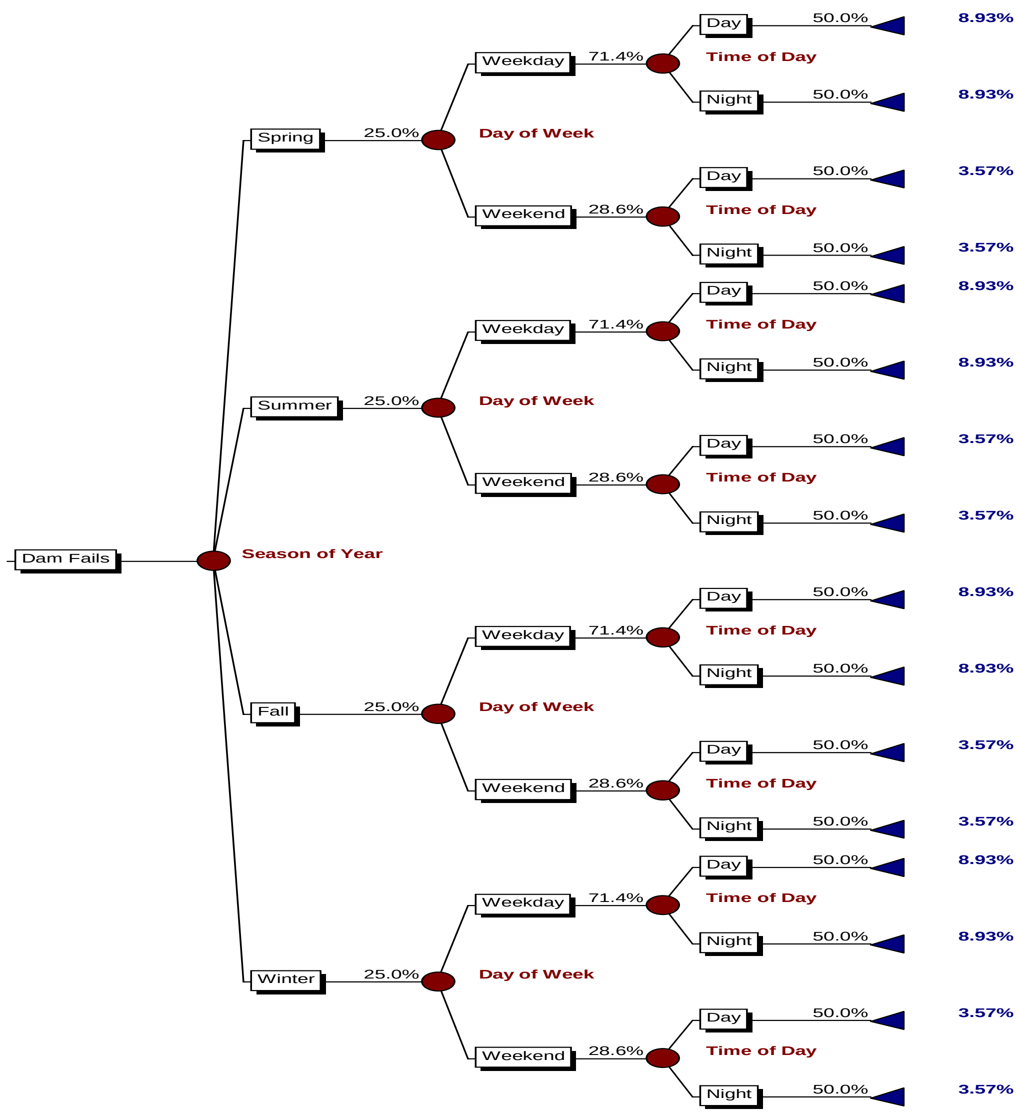
When it is suspected that time factors will significantly affect the PAR (and when there is sufficient data to perform such an exercise), a logic diagram similar to an event tree can be used to estimate a distribution for the PAR variation (see figure 1 below). This logic diagram could have four branches for the seasons. Each seasonal branch could have two branches for weekday/weekend, and each of these could have two branches for day vs. night. Ranges for populations at risk could then be estimated for each of the 16 end branches. Each PAR associated with the given time frame would be multiplied by the proportion of time represented by the branch, and the weighted PAR numbers would be summed to obtain the PAR's weighted average for the entire year.

Even if the PAR is not affected by these time factors, the time factors may affect the potential warning time. More will be provided on this in the section on warning time presented below.

Suggestions for CFR level risk analyses:

1. If the transient population (campers, people fishing, etc.) are a significant portion of the PAR, carry through a best-case / worst-case estimate based on the times of the year when the facilities are empty or most crowded.

Figure 1. Breakdown of a year into time periods when there may be different populations at risk.



IV. Estimate Population at Risk (PAR) for each scenario

There are many reasons why people are located in an area that could be inundated by a dam break flood: they may live, work, or go to school in the area; they may spend the day fishing or spend several days at a campsite; they may be driving on roads or walking on scenic trails; they may be confined in places such as hospitals or prisons. Rapid economic development in some localities might cause a future PAR to be much greater than the present PAR.

A. Sources of Information on Population at Risk

In order to estimate the potential life loss for a given dam-break situation, the number of people exposed to the flooding need to be identified. These people can live in, work in, or travel through the inundated area.

PAR information is typically scarce or not available. Sometimes an old hazard analysis or a potential life loss estimate has been conducted, but in most cases, the desired information needs to be generated. In the past, the hazard analysis asked the question “is there significant incremental life loss if the dam were to fail?” A simple yes/no answer was sufficient. Evaluating consequences for a risk analysis asks the slightly different question: “what is the amount of life loss that is likely?” Different tools or degrees of investigation intensity are required to answer the two questions.

The traditional way to generate PAR information has been to divide the river downstream from the dam into reaches. The basis for the division would be distinguishably different centers of high, medium and low population density or suspected differences in flood intensity, warning characteristics, or population reaction. The inundation boundary maps reported in the SOP often have towns, individual houses and topographic data on them. Each type of population identified in the various reaches can have several sources of information.

The partitioning should end at a distance downstream from the dam where flood waters are no longer considered life threatening, or where there are means to evacuate the entire PAR. Fifteen miles downstream from the dam has typically been chosen as a cutoff point since flood wave peaks travel on average at about 10 miles per hour, and about 90 minutes of warning time is usually sufficient to evacuate the PAR. It may be possible that failure could initiate undetected, particularly at remote dam sites, and that the first notice of increasing flood stage would come at a population center located some distance from the dam. If this is a likely scenario, the 15 miles should be measured from a point where detection of abnormal flow behavior is likely to be first detected. When it is possible that the flood wave could travel faster that 10 miles per hour, the distance should be increased accordingly. Also, the case histories upon which Wayne Graham based his life-loss factors only include populations up to about 35,000. Consideration should be given to situations where there are hundreds of thousands of people in inundation areas located more than 15 miles downstream from the point of first detection. In these cases, the PAR would be those people not evacuated in the time it takes for the flood wave to arrive. There is no guidance available at this point on the amount of time it would take to evacuate populations of various sizes. Local emergency response personnel may be of some assistance for this estimate.

The census of fully- or partially-inundated towns can be obtained from almanacs or from the index in the back of a road atlas. Census data is also available on the Internet (www.census.gov/cgi-bin/gazetteer – type in the town name – look at the map to see what the boundaries are of the unit you have specified – lookup table STF1A – check the “persons” box - submit). The PAR from a town has typically been estimated by multiplying the population of the town by the fraction of the town’s area inundated by the dam-break flood. The PAR in low-density areas has been estimated by counting houses on the topographic map and multiplying by a residents-per-house factor (typically 1.7 but this multiplier can also be obtained from the census tables).

Recently, Geographic Information System (GIS) services have become available that can create many layers of information on top of a topographic base map. The intersection of census block information and inundation boundaries digitized from the SOP maps is used to generate a "resident" population at risk. This analysis tool does not provide an estimate of the "transient" population at risk, those who might be in the inundation area on a temporary basis. The reported numbers are determined as follows. First, the vector flood boundary is overlain on a one-meter resolution, U.S.G.S,. digital, orthophotographic quarter quadrangle (DOQQ) image on the computer screen. Populations in wholly inundated census blocks are said to be at 100% risk. The total populations for each of these blocks are summed. Next, partially inundated blocks are examined individually to estimate what fraction of residences in each is within the flood boundary. This fraction is multiplied by the total block population to arrive at a PAR. Fractional census block populations are summed together and added to the total for the fully inundated blocks. Total PAR figures are reported by river reach. When the flood modeling software generates maximum depth contours, as MIKE21 does, the GIS analyst can also report populations at risk by water depth.

The discussion so far has focused on permanent residents within the inundated areas. The information needed to estimate transient PAR may come from many different sources. Area office personnel may have knowledge of campground or daytime usage when considering recreational use of Reclamation facilities. State Park or National Park personnel would have an idea about the seasonal, weekend vs. weekday use in their campgrounds. In some very small communities, the post office manager might have information on seasonal use of cabins. Talking to local business people can also verify verbal evidence regarding recreational use.

The state transportation office has information on the usage of major highways. Information is typically available broken down into time of day, day of the week, and by month. For some roads, estimates of usage have been projected into the future.

However the PAR information is generated, it is essential to verify the assumptions made in the office by checking the information in person. Estimating PAR by counting houses on a topographic map assumes that the number of houses has not changed since the map was created or last revised. Rapid growth in certain areas is not accounted for in the 1990 census data. Multiplying the inundated fraction of a town by its population assumes the residential and business land use is evenly situated within the town. **The main purpose for driving the floodplain below the dam during the CFR dam inspection trip is to check the assumptions made for the PAR estimate.** A website that can assist verification is http://terraserver.homeadvisor.msn.com/ where there are fairly recent aerial photographs cross-referenced with topography maps. Remember that since warning time and ability to successfully evacuate both increase with distance from the dam, the PAR estimate's accuracy is more important in the first reaches below the dam.

B. Suggestions for CFR level risk analyses

1. Subdivide the river into several reaches. Consider reaches to a distance of approximately 15 miles downstream from the first likely detection location (farther if appropriate).
2. Estimate the PAR in each reach. Select a reasonably high estimate and a reasonable low estimate.
3. Consider the proportion of the PAR exposed to moderate severity and low severity flooding (these terms are explained in section VI below).
4. Try to make the estimate before the examination visit, and then adjust the estimate based on what is observed when driving the area below the dam.

V. Determine warning time scenarios

In its simplest form, warning time is the amount of time between the notification given to a population to evacuate and the arrival of the flood wave at that population's location. Life loss has been observed to be inversely proportional to the amount of warning time available to the PAR. Upon closer examination, the warning time concept is not so simple. When evaluating historic dam failure cases, a convention is typically chosen that assumes the clock starts at the time when a concerted effort begins to get people out of the way. But what kind of warning was issued? Was it one that clearly impressed people that if they do not leave as quickly as possible, they will surely die? How much of a river reach and how many different population concentrations should be included when deciding what value to assume for the warning time in any given case history?

The warning time concept is even more complex when one attempts to predict what might happen in the future if a dam were to break. With a case history, the state of all the various parameters affecting warning and evacuation is fixed, even if we do not always know that state very precisely. When predicting the future, we have to surmise the chain of events leading to the decision to warn the downstream population to evacuate. How long before authorities can be aware a situation is developing, what types of evidence make it clear the observed behavior will lead to a dam failure, who will assume the responsibility to order an evacuation and how quickly can they be informed enough to make the decision? In the mean time, the dam would be failing at some unknown rate. We must surmise how long it will take for a full breach to form in the dam, and then analyze how the reservoir release might be routed downstream from the dam.

A. Information Sources for Estimating Warning Time

Primary factors that influence warning time include the ability to detect a developing failure, the procedures to make decisions regarding evacuation, and the ability to notify the PAR once the decision to evacuate has been made. Physical factors that influence the amount of warning time depend on how rapidly life-threatening flood intensities can materialize and how long it takes for the flood waters to travel to the PAR. Human intervention in the dam failure can increase these physical factors. Though, technically, evacuation begins after warning has been given, the ability to evacuate can be considered a part of effective warning time and can also affect potential life loss.

Detection depends on the frequency and extent of monitoring activities at the dam. A dam observed daily would have much better discovery opportunities than one visited monthly. An automated monitoring and alarm system should increase warning time if it is reliable and is properly designed, maintained, and situated. The automated system must have predetermined levels which, when reached, notify an appropriate person. The detection devices must be maintained regularly and located so they will not be destroyed by the hazardous event. An extremely remote dam requiring long travel time for a visual inspection, or one located where access is impossible because the only access road is inundated by flooding are situations that might decrease warning time because detection may be delayed.

Decision time can depend on the status of emergency preparedness. Typical response procedures discussed in advance of a potential problem might save time if something happens at the dam, so the decision to evacuate may depend on the status of the Emergency Action Plan (EAP) for the dam. Not having any plans could have a negative effect on decision time. The benefit from having a written plan depends on who participated when the plan was written, and whether it is readily accessible to those who might detect a developing problem. If the EAP has been recently exercised in a mock trial, the local decision-makers will certainly be better prepared to make quick decisions. Decision time also can depend on the ease of finding a person of authority, and on the quality of judgement and the decisiveness of that authority.

Notification time depends on the resources available to spread the word effectively. Transient populations involved in recreational activities may be difficult to notify. Similarly, sparsely populated areas may be limited to notification by telephone. As population density increases, additional notification media become available, and there may be more emergency response personnel available. Often not factored into life loss considerations, but very important nonetheless, the flood severity nature understood by evacuees when the evacuation message is delivered affects the population’s willingness to leave. Human factors such as these are very difficult to predict, so it is appropriate to estimate ranges that may bound likely scenarios.

Evacuation ability depends on the nature of the routes available during or after an event. Populations located in steep-sided canyons with no exit except at the mouth of the canyon would have the most difficulty escaping. Likewise, when a large population must use a single highway to get out, traffic congestion would make evacuation difficult. Evacuation would be difficult even if there are many escape routes but they are blocked as a result of the event (eg. roads washed out during floods, bridges destroyed during earthquake, etc.). In other cases, people can very easily get out of the inundation area by climbing to higher ground even though roads along the river are washed out.

The amount of advance warning also depends on the flood wave travel time with respect to the PAR’s location downstream from the dam. Those close to the dam will have a smaller time margin.

The type of failure mode can influence warning time. Extreme flood events in very large drainage basins take significant time to develop, during which heightened awareness and monitoring may take place. Overtopping situations may have several hours or even days of advance warning under these conditions. In small basins, the floods develop much quicker, so life-threatening events would have less advance warning. Piping failures would, under most conditions, give many hours or even days of advance warning if an effective monitoring system exists at the dam. Earthquake failure modes are expected to give the least amount of warning, unless the downstream public is aware that the dam threatening them has a potential to fail under earthquake loading and they are prepared to evacuate without notification (the earthquake itself would then be the notification).

Estimation of warning time should involve individuals who are familiar with the various components described above. If there is one, the dam tender should be consulted. Area or Regional Office personnel, or others intimately familiar with the EAP, should be consulted or, even better, should participate in the risk analysis during this discussion.

The risk analysis team should work through best case / worst case scenarios when estimating warning time. A best case scenario might be: The dam tender is on the dam's abutment when an earthquake happens. The downstream face of the dam slides, allowing reservoir water to overtop the remnant crest. The dam tender has a cell phone or radio. The communication system still operates. The dam tender knows which emergency preparedness official to call. The official is successfully contacted. There has been a tabletop exercise recently, so the official knows just what to do. The warning is given in such a way that the people at risk react immediately. They know where to go. Evacuation is not hampered by infrastructure destruction.

Each component of the warning / evacuation discussed in the best-case scenario or worst-case scenario would be assigned a time value, and the component times would be summed. The breach development time and flood wave travel time would be discussed and compared to the time available for warning and evacuation.

Some suggestions regarding warning time considerations appear in Table 7 (at the end of this document). Using this table has the advantage of taking less time, and might provide some degree of consistency to the warning time calculation. On the other hand, its use doesn't allow for site-specific factors that may be extremely important.

As a matter of convention, the method outlined in Section VI below for estimating life loss given PAR and warning assumptions uses three time categories: "none" (zero to 15 minutes), "some" (15 to 60 minutes) or "adequate" (greater than 60 minutes).

B. Suggestions for CFR level risk analyses

1. Estimate first likely detection location. (Consider best case / worst case.)
2. Estimate travel time downstream from there (flood waves travel about ten mph)
3. If the dam breach takes a significant amount of time to form, the flood peak flow quantity will be delayed. Consider making an adjustment for this.

4. Consider best case / worst case scenarios for detection, decision, notification, and evacuation times.
5. Use judgement to proportion the warning time into the categories “none” (zero to fifteen minutes), “some” (fifteen minutes to one hour), or “adequate” (more than one hour). Judgement can be used to extend the one hour as the boundary between “some” and “adequate” when the PAR is very large. Consider best case / worst case, but in each case the proportions divided into the three categories (as percentages) must add to one.

VI. Apply empirically based equations to estimate potential life loss

A. Reclamation’s Revised Empirical Model

Reclamation has moved away from using DeKay and McClelland’s equations based on statistical regression, towards the empirical approach devised by Graham. DeKay and McClelland’s treatment of the case history data produced a correlation between PAR, WT and life loss that considers, as one unit, the entire river reach. However, when predicting potential life loss, the risk analyst frequently would like to partition the river according to their perception of the expected differences in flood lethality or population center response. Proper use of DeKay and McClelland’s model does not allow this. Furthermore, since a very limited number of case histories were included in the statistical regression, very wide confidence bounds are the result. The data include no cases of life loss in dambreaks from earthquakes (since there are none), and there are no cases where the population at risk was greater than 35,000.

These problems make the use of DeKay and McClelland’s model questionable as a predictor of life loss. Their method was useful to Reclamation when it was trying to answer a yes or no question: “Is there significant incremental life loss?” Their method is not as useful when answering the question “how much life loss is likely?” In an attempt to provide a way to estimate life loss that might be more generally applicable, Graham reviewed the case history data and devised a model that can be used to estimate potential life loss for individual population centers.

Graham analyzed nearly all U.S. dam failures (and some foreign dam failures) causing 50 or more fatalities. For each of these events, the area downstream was divided into different geographic areas and information on flood severity, amount of warning, and the nature of the warning were examined. Graham identified fifteen different combinations of these parameters, classified population concentrations from the case histories in these categories, and determined life loss as a percent of people at risk for each population. Graham used these “type cases” to propose ranges for the expected potential life loss as a decimal fraction of PAR for each category.

The flood intensity is the most important factor that determines the fatality rate that is likely to occur. Fast flowing and deep water inundating areas where the population is at risk would cause much more life loss than shallow, slow moving water. Therefore, the first step in Graham’s life loss estimation model requires a flood severity be assigned to each PAR group being considered. “Low Severity” occurs when no buildings are washed off their foundations. “Medium Severity” occurs when homes are destroyed but trees or mangled homes remain for people to seek refuge in or on.

“High Severity” occurs when the flood sweeps the area clean and nothing remains. Graham gives additional guidance on this category: “Use high flood severity only for locations flooded by the near instantaneous failure of a concrete dam, or an earthfill dam that goes out in seconds rather than minutes or hours. In addition, the flooding caused by the dam failure should sweep the area clean and little or no evidence of the prior human habitation remains after the floodwater recedes. Nearly all the events used in defining this category caused very deep floodwater that reached its ultimate height in just a few minutes.”

Warning Time is the second factor that is used to determine the fatality rate. Graham considers the data too sparse to be able to treat warning time as a continuous variable. The perception of warning time is placed in purposefully imprecise categories. “No Warning” means that no warning is issued by the media or official sources; only the possible sight or sound of the approaching flooding serves as a warning. “Some Warning” means that officials or the media begin warning in the particular area, say 15 to 60 minutes before the floodwater arrives. Some people will learn of the flooding indirectly when contacted by friends, neighbors or relatives. “Adequate Warning” means that officials or the media begin warning in the particular area more than 60 minutes before the floodwater arrives. Some people will learn of the flooding indirectly when contacted by friends, neighbors, or relatives.

Flood Severity Understanding is the last factor considered by Graham as influencing the fatality rate. The relative understanding of the flood severity is a function of the distance or time from the dam failure or the source of the flooding. The farther one is from the source of the flooding, the greater the likelihood that the warning will be precise and accurate. This is because people have seen the flooding in upstream areas and the warnings are adjusted to reflect the actual danger. A warning of potential flooding, before it occurs, may not be understood by the warning issuers and would therefore be difficult to describe. Recipients of this warning will therefore not get a true picture of the flooding about to occur and may not evacuate at all or not as quickly as they should. “Vague Understanding” of flood severity means that the warning issuers have not yet seen an actual dam failure or do not comprehend the true magnitude of the flooding. “Precise Understanding” of flood severity means that the warning issuers have an excellent understanding of the flooding due to observations of the flooding made by themselves or by others. It seems probable that evacuation will be more complete as the warnings become more precise and believable due to the confirmation of flooding observed in upstream areas.

Table 8 (at the end of this document) contains recommended fatality rates for each of the 15 different combinations of flood severity, warning time, and flood severity understanding.

B. Suggestions for CFR level risk analyses

1. Use the procedures described above to estimate a best case and a worst case for PAR ("highly optimistic" and "highly pessimistic" might be more appropriate terms as they can not be considered absolute terms as can "best case" and "worst case").

2. For an extreme best case life loss estimate, use the best case PAR estimate, assume 100 percent are exposed to low severity flooding, assume adequate warning, and assume Graham's low value for fatality rate.
3. For an extreme worst case life loss estimate, use the worst case PAR estimate, assume 100 percent exposed to moderate severity flooding, assume no warning, and use Graham's extreme high value for fatality rate (.35).
4. An estimate of the range of values for potential life loss would be between these extreme values. The extreme values at the end points would have a low likelihood of being a representative value. Therefore, a third estimate is required. The third estimate would be obtained by using judgement to determine a "reasonable" value for PAR, flood severity, warning time, and fatality rate. The resulting life loss estimate would indicate to the decision maker where in the range between best and worst cases the author of the CFR thought the actual value might be. It is important to estimate the extreme values before deciding upon a best estimate. Otherwise, people tend to anchor on the best estimate and then predict extremes that are not far enough from the best estimate to accurately represent the uncertainty.

VII. Evaluate uncertainty

A. Baseline Risk Analysis or Risk Reduction Analysis

There is a large degree of uncertainty associated with each aspect of Graham's life loss estimate method. During an extensive Baseline Risk or Risk Reduction analysis, the uncertainty should be treated explicitly. This should be easy to do since the risk analysis team has by this time considered ranges for values discussed during each step in the life loss analysis.

@Risk is an excellent tool for conducting both an uncertainty analysis and a sensitivity analysis. There can be a separate event tree for each failure mode. Likewise, different expectations for dam breach formation rates can be analyzed using separate event trees. Reasons for expecting large changes in PAR ranges, such as seasonal, weekly, or time-of-day variations will add branches to a given tree. The principle variables in the event tree are PAR, flood severity, and warning time. Graham's ranges for fatality rates are also a part of the analysis. An example of an event tree used to calculate the range of expected life loss for Medicine Creek Dam is given below.

The results from an @Risk Monte Carlo simulation can be plotted as either a probability distribution or as a cumulative distribution. The probability distribution form is the most useful graphical way to communicate the expected range of life loss for a given failure scenario. The cumulative distribution should be used as input to a separate Monte Carlo simulation that analyzes the joint probability of dam failure and probability of life loss given dam failure for a given failure scenario.

A. Suggestions for CFR level risk analysis

1. report zero lives lost as the absolute "best case".
2. report a "worst case" (WC) using the highest PAR, the most severe flood severity category, no warning, vague understanding, and the highest end of Wayne Graham's fatality rate. If there is no chance the flood severity at a given PAR can be "moderate", use "low" severity for that particular PAR in the worst case scenario.
3. choose a "best estimate" (BE) or "most reasonable estimate" after thinking through what might be the most extreme end points and then going back through Graham's process using what might be a most reasonable estimate for each variable.